Shot noise in resonant tunneling through a zero-dimensional state with a complex energy spectrum

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We investigate the noise properties of a $GaAs/Al_xGa_{1-x}As$ resonant-tunneling structure at bias voltages where the current characteristic is determined by single electron tunneling. We discuss the suppression of the shot noise in the framework of a coupled two-state system. For large bias voltages we observe super-Poissonian shot noise up to values of the Fano factor $\alpha \approx 10$.

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Shot noise allows for a direct measurement of the correlation in a current of discrete charges. In the case of a totally uncorrelated current, one observes the so-called full or Poissonian shot noise.[1] The corresponding noise power S displays a linear dependence $S=2eI$ on the stationary current I as long as the applied bias voltage V_{SD} is large compared to the thermal energy: $eV_{SD} \gg 2k_BT$.[2] Full current shot noise arises, e.g., in a single tunneling barrier, since the tunneling process of different electrons are independent of each other.

However, if an additional source of *negative* correlation is introduced the noise amplitude was shown to be reduced.[3,4] For resonant tunneling through a double-barrier structure this is attributed to the dependency of successive tunneling events caused by the finite dwell time of the resonant state.[5,6] This suppression of the shot noise has also been observed for resonant tunneling through zero-dimensional systems.[7,8] For the opposite case of a *positive* correlation between individual tunneling events the noise power can even become *super*-Poissonian.[9,10]

We report on noise measurements of a resonant-tunneling double-barrier structure. Under certain bias conditions the tunneling current through our sample flows through a single zero-dimensional state.[13,14] Therefore we are dealing with $3d$-$0d$-$3d$ tunneling in contrast to the above-mentioned experimental studies where the tunneling takes place through a two-dimensional subband ($3d$-$2d$-$3d$).[5,6]

Our sample consists of a nearly symmetric double-barrier resonant-tunneling structure grown by molecular-beam epitaxy on a n^+-type GaAs substrate [see Fig. 1(a)]. The heterostructure is formed by a 10-nm-wide GaAs quantum well sandwiched between two $Al_{0.3}Ga_{0.7}As$-tunneling barriers of 5 and 6 nm thickness. The contacts consist of 300-nm-thick GaAs layers doped with Si (4×10^{17} cm^{-3}) and they are separated from the active region by a 7 nm thick undoped GaAs spacer layer. The geometrical diameter of the diode is 1 μm.

The current-voltage (I-V) characteristic is plotted in Fig. 1(c). The upper inset shows the characteristic shape of the resonance due to tunneling through the two-dimensional subband at $V_{SD}=\pm130$ mV. However, we concentrate our measurements on small bias voltages $|V_{SD}| \leq 10$ mV, where we find a pronounced current step (marked with "X"). This feature indicates the presence of at least one single impurity in the nominally undoped GaAs, as depicted schematically in Fig. 1(b). Such impurity states with an energy lower than the quantum well in between the barriers most likely stem from unintended donor atoms within the well.[11–14]

The I-Vcurve is slightly asymmetric regarding both bias polarities. We attribute this to the different transmission coefficients of both tunneling barriers due to their differing growth thicknesses. In our experiment positive bias voltage means always that tunneling occurs first through the barrier of lower transmission. Therefore $V_{SD}>0$ corresponds to current flow in noncharging direction since the resonant state is more often empty during a certain time interval than being occupied. Consequently, $V_{SD}<0$ implies charging direction, respectively.

In an external magnetic field in parallel to the direction of the tunneling current I the position of the current step X is shifted to higher voltages, overall following a parabolic dependence as can be seen from the lower inset of Fig. 1(c). This is caused by the diamagnetic shift of the resonant state

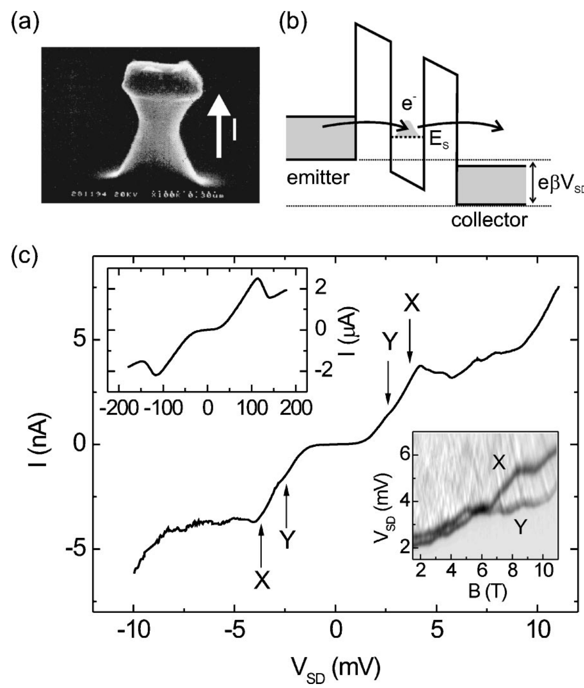

FIG. 1. (a) SEM picture of the resonant tunneling diode. (b) Schematical diagram of the energy band. (c) I-V characteristic measured at $T=1.3$ K. Upper inset: I-V characteristic of the sample for larger applied voltages. Lower inset: Differential conductance at a temperature of $T=50$ mK in an external magnetic field in parallel to the tunneling current.

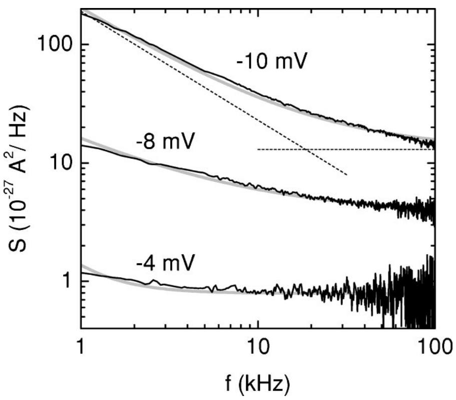

FIG. 2. Measured noise spectra for different values of the bias voltage V_{SD}. The gray curves are the results of fitting the function $A/f^{\chi}+S_0$ to the data. The dashed lines demonstrate the contributions of 1/f noise (angular line) and shot noise (horizontal line) to the fit for 10 mV.

E_S. This allows us to estimate the classical diameter[13] of the zero-dimensional state to $r\sim 10$ nm. Additionally, the *I-V*-curve does reveal a second weak structure which is marked with "*Y*" in Fig. 1(c). It is more pronounced for charging direction ($V_{SD}<0$). As can be seen in the lower inset of Fig. 1(c), in the magnetospectroscopy this feature first moves parallel to *X*. At $B=6$ T both features merge before splitting again at higher field, but still producing correlated kinks, e.g., at 8 and 10 T. Therefore *X* and *Y* are presumably not caused by independent impurities but stem from a two-level system.[15]

The noise experiments are performed in a ^{4}He bath cryostat with a variable temperature insert. The sample is always immersed in liquid helium. This allows for measurements at temperatures between 1.4 K and 4 K under stable conditions. The bias voltage V_{SD} is applied between the source and drain electrodes by means of a filtered dc-voltage source. The noise signal is detected by a low-noise current amplifier.[8,16] The amplifier output is fed into a voltmeter for measuring the stationary current through the sample and into a fast Fourier-transform analyzer (FFT) to extract the noise spectra in a frequency range from 0.4 to 102 kHz with 0.13 kHz resolution. The amplifier and the input stages of the FFT have been tested for linearity in the range of interest, overall calibration has been verified by measuring the thermal noise of thick film resistors.

In Fig. 2 we show exemplarily noise spectra at different bias voltages for charging direction. For $|V_{SD}|<5$ mV the observed signal is mainly determined by the frequency independent shot noise. Only below frequencies $f\lesssim 10$ kHz we find contributions of $1/f$ noise. To characterize the amplitude of the shot noise we use the so-called Fano factor α which is defined by normalizing the measured noise power density S to the Poissonian value $2eI$: $\alpha=S/2eI$ with e the electron charge and I the stationary (dc) current. For determining S we average the noise spectra over frequencies larger than the cut-off frequency of the $1/f$ noise.

As the magnitude of the bias voltage is increased, the intensity of $1/f$ noise rises with an approximate quadratic dependence on current I (data not shown). At bias voltages above $|V_{SD}|=8$ mV a direct readout of the Fano factor becomes impossible since $1/f$ noise is no longer negligible. However, by fitting the noise spectra with the function $S(f)=A/f^{\chi}+S_0$ we can still extract the amplitude of the shot noise S_0: Since the noise processes leading to shot noise and $1/f$ noise are uncorrelated to each other, their corresponding noise power add up. Accordingly, the fitting parameter S_0 is the amplitude of the frequency independent shot noise power. For the exponent χ characterizing the $1/f$ noise we find $\chi\approx 1$ in agreement with the literature.[17–19] That fit also reveals that even for the strongest observed $1/f$ noise at $V_{sd}=-10$ mV the shot noise exceeds the $1/f$ noise for $f>20$ kHz. Therefore we can extract the shot noise contribution reliably.

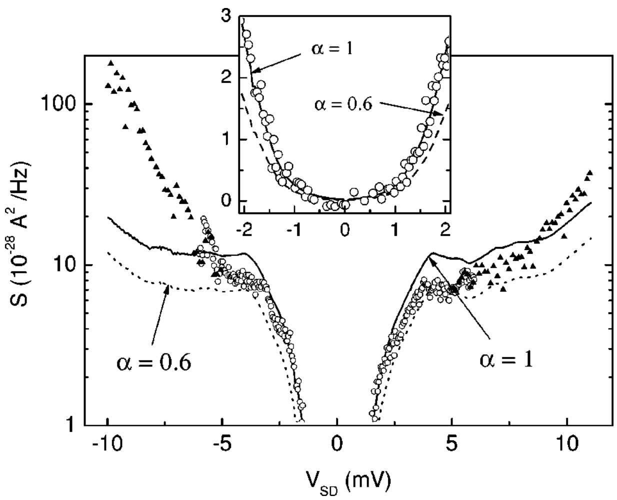

FIG. 3. Shot noise measured as function of bias voltage V_{SD}. For bias voltages $|V_{SD}|<6$ mV the shot noise amplitude has been defined by averaging the spectra over frequencies above the cut-off value of $1/f$ noise (open circles). At higher bias voltages a fitting procedure has been used (black triangles, see text). Inset: Shot noise in a linear scale for small bias voltage.

In Fig. 3 we plot the measured shot noise power of the sample for $|V_{SD}|\leqslant 10$ mV. Note the good agreement between the results for the shot noise power extracted from averaging the spectra (open circles) and from the fitting procedure (black triangles) in the bias range where both overlap. Therefore we conclude that the shot noise can be extracted even under bias conditions where it is masked by $1/f$ noise to a large extent.

For comparison we show the theoretically expected Poissonian value for full shot noise ($\alpha=1$) calculated from the measured dc current I using $S=\alpha(2eI)\cot(eV_{SD}/2k_BT)$ with the temperature T and Boltzmann's constant k_B.[2] As can be seen from the inset in Fig. 3 we observe full shot noise at bias voltages smaller than $|V_{SD}|<2$ mV. But with increasing absolute value of the bias voltage the noise is suppressed below its Poissonian value $\alpha=1$. Overall the suppression is more pronounced for noncharging direction ($V_{SD}>0$). In Fig. 3 also the theoretically expected noise power for a suppression of $\alpha=0.6$ is shown by the dashed line. This minimal value of the Fano factor $\alpha\approx 0.6$ is found on the current plateau 4 mV$<V_{SD}<$5 mV. This can be seen in more detail

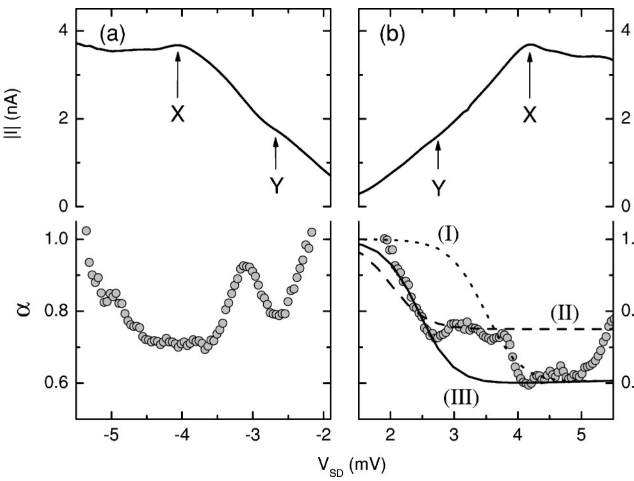

FIG. 4. Behavior of the Fano factor α for the crossover from subresonant to resonant transport in charging (a) and noncharging direction (b). The data has been smoothed with a seven-point boxcar average. For the smoothed α we estimate the error to $|\delta\alpha|<0.05$ for $V_{SD}<3$ mV and $|\delta\alpha|<0.03$ for $V_{SD}>3$ mV. For comparison with the data we show the theoretically expected characteristics under different assumptions (see text).

in Fig. 4(b), where the Fano factor for noncharging direction is depicted. It has been shown theoretically that the suppression of shot noise for a resonant state E_S is linked to the asymmetry of both tunneling barriers:[2]

$$\alpha=\frac{\Theta_E^2+\Theta_C^2}{(\Theta_E+\Theta_C)^2}. \tag{1}$$

Θ_E and Θ_C are the tunneling rates through emitter and collector barrier, respectively. Responsible for this suppression is the Pauli exclusion principle: The tunneling of an electron from the emitter into the quantum dot (QD) is forbidden as long as the QD state E_S is occupied. This results in an anticorrelation of successive tunneling events. The maximal suppression of $\alpha=1/2$ is expected for symmetric barriers ($\Theta_E=\Theta_C$). However, for a tunneling structure of high asymmetry (e.g., $\Theta_E\gg\Theta_C$) full Poissonian shot noise ($\alpha=1$) would be recovered, since then the transport will be controlled solely by one barrier.

From the growth data of the sample we can compute the tunneling rates Θ_E and Θ_C. This is done by a self-consistent solution of Poisson and Schrödinger equation. Using these values with Eq. (1) results in $\alpha=0.6$, which is in good agreement with the experimental result on the pronounced current step at voltages between 4 and 5 mV [see Fig. 4(b)].

In Fig. 4(b) the behavior of the Fano factor is plotted for the bias range, where the crossover into resonant transport occurs. For $V_{SD}<2$ mV we observe full shot noise. Above $V_{SD}=2$ mV the Fano factor is reduced in two steps: For 3 mV$\lesssim V_{SD}\lesssim$4 mV a value of $\alpha\approx0.75$ is present. This suppression sets in precisely where a weak resonance can be seen in the I-Vcharacteristics (marked with Y). For 4 mV $\lesssim V_{SD}\lesssim$5 mV the above mentioned value of $\alpha\approx0.6$ is found, which is consistent with the growth data of the tunneling structure. Increasing the bias voltage further results again in a rise of the Fano factor.

It has been shown analytically by Kiesslich *et al.*[20] that the bias dependence of α can be described by the expression

$$\alpha=1-\frac{2\Theta_E\Theta_C}{(\Theta_E+\Theta_C)^2}f_E, \tag{2}$$

where $f_E^{-1}=1+\exp[(E_S-\beta eV_{SD})/k_BT]$ is the Fermi function of the emitter contact (we relate the energies to $E_F=0$) and β the voltage-to-energy conversion factor for the tunneling structure. In case of resonance and $T=0$ the emitter occupancy at $E=E_S$ is maximal $[f_E(E_S)=1]$ and Eq. (2) reduces to Eq. (1). At finite temperature $T>0$ the crossover from Poissonian to sub-Poissonian shot noise is smeared out by the thermal energy distribution of the emitter electrons.

Now we will discuss the crossover behavior of the Fano factor as observed in Fig. 4(b) under different assumptions: At first we consider the features X and Y as being caused by tunneling through two independent resonant states. For each we expect a crossover to the suppressed shot noise as described by Eq. (2). This is shown by the two curves marked as (I) and (II) in Fig. 4(b). In case of (I) we used the calculated values for $\Theta_E(V_{SD})$ and $\Theta_C(V_{SD})$ and chose a value for E_S so that the crossover from $\alpha=0.75$ to $\alpha=0.6$ coincides with the shape of Eq. (2). For (II) we change the asymmetry factor to fit a suppression of $\alpha=0.75$. In both cases the crossover of the measured Fano factor occurs significantly steeper than expected from the form of (I) and (II), respectively.

However, if we consider just the dominant feature X in conjunction with the calculated tunneling rates for a suppression of $\alpha=0.6$ the crossover from $\alpha=1$ below $V_{SD}=2$ mV to $\alpha=0.6$ for $V_{SD}=4$ mV can be described quite satisfactorily, of course with a deviation in the bias range 3 mV$\lesssim V_{SD}\lesssim$4 mV [curve (III) in Fig. 4(b)]. Thus the behavior of the Fano factor cannot be explained by two independent states. Instead we conclude, that the features X and Y are correlated in a twofold energy spectrum, in agreement with our discussion of the magnetotransport spectroscopy shown in Fig. 1(c). The assumption of a correlated two-level system is also stressed by the fact that the general shape of the Fano factor seems to be mainly determined by a single Fermi-function [(III) in Fig. 4(b)]. Whereas the increase of the Fano factor up to $\alpha\approx0.75$ around $V_{SD}\approx3.5$ mV may be caused by correlation effects on the current flow due to the twofold energy spectrum of the resonant state. For example, it has been shown that a capacitive coupling of two resonant states influences the corresponding shot noise properties.[21]

We discuss now the transport in charging direction ($V_{SD}<0$): The observed shot noise is larger compared to noncharging direction as can be seen from Fig. 4. In the theoretical picture for resonant tunneling [Eqs. (1) and (2)] the Fano factor α is symmetrical to reversal of bias voltage. However, in a coupled system of two resonant states of different energies the Fano factor can be enhanced for charging transport.[21] We view that as a further affirmation of the above described perception of a resonant state with a twofold energy spectrum.

Finally we will turn to the discussion of the super-Poissonian shot noise ($\alpha > 1$). It is evident from Fig. 3 that for charging direction $V_{SD} < 0$ the Fano factor α increases at $V_{SD} < -6$ mV above $\alpha = 1$ up to values of $\alpha \approx 10$ at $V_{SD} = -10$ mV. In contrast this effect is only weakly developed for noncharging direction ($\alpha = 1.5$ at $V_{SD} = +10$ mV).

Up to now super-Poissonian shot noise has been experimentally observed for transport through the two-dimensional subband of a resonant tunneling structure.[9,10] The effect occurs in the negative differential region of the I-V characteristics. It can be explained by a feedback mechanism that is caused by the charging of the resonant state and a consequent fluctuation of the subband energy. This leads to a *positive* correlation in the current flow and consequently the Fano factor becomes super-Poissonian $\alpha > 1$.[9,22]

We may speculate that in our sample a similar mechanism occurs although we are dealing with a zero-dimensional state. This assumption is underlined by the fact that we find time dependent fluctuations in the I-V characteristics for charging direction. These appear precisely at the bias voltage where the Fano factor crosses over from a sub- to a super-Poissonian value [see Figs. 1(c) and 3]. For noncharging direction we observe no fluctuations of the stationary current and the Fano factor does not significantly exceed $\alpha = 1$.

In conclusion we have analyzed the shot noise properties of resonant transport through a zero-dimensional state that is formed by a impurity situated within the quantum well of a tunneling structure. In the magnetospectroscopy a twofold energy spectrum of the resonant state could be identified. The minimal observed value for the Fano factor of $\alpha = 0.6$ does coincide with what is theoretically expected for the asymmetry of the tunneling structure as known from the growth data. Although the general features of the crossover from the full shot noise $\alpha = 1$ at low bias voltage into the suppression of $\alpha = 0.6$ can be satisfactorily described by a single Fermi function, we observe deviations that we attribute to the complex nature of the resonant state.

Additionally we observe a super-Poissonian value ($\alpha > 1$) of the shot noise for large bias voltage in charging direction, that is presumably caused by charging effects.

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[1] W. Schottky, Ann. Phys. (Leipzig) **57**, 541 (1918).

[2] Y.M. Blanter and M. Büttiker, Phys. Rep. **336**, 1 (2000).

[3] Yuang P. Li, A. Zaslavsky, D.C. Tsui, M. Santos, and M. Shayegan, Phys. Rev. B **41**, 8388 (1988).

[4] H.C. Liu, J. Li, G.C. Aers, C.R. Leavens, M. Buchanan, and Z.R. Wasilewski, Phys. Rev. B **51**, 5116 (1995).

[5] L.Y. Chen and C.S. Ting, Phys. Rev. B **43**, R4534 (1991).

[6] J.H. Davies, P. Hyldgaard, S. Hershfield, and J.W. Wilkins, Phys. Rev. B **46**, 9620 (1992).

[7] H. Birk, M.J.M. de Jong, and C. Schönenberger, Phys. Rev. Lett. **75**, 1610 (1995).

[8] A. Nauen, I. Hapke-Wurst, F. Hohls, U. Zeitler, R.J. Haug, and K. Pierz, Phys. Rev. B **66**, R161303 (2002).

[9] G. Iannaccone, G. Lombardi, M. Macucci, and B. Pellegrini, Phys. Rev. Lett. **80**, 1054 (1998).

[10] V.V. Kuznetsov, E.E. Mendez, J.D. Bruno, and J.T. Pham, Phys. Rev. B **58**, R10 159 (1998).

[11] M.W. Dellow, P.H. Beton, C.J.G.M. Langerak, T.J. Foster, P.C. Main, L. Eaves, M. Henini, S.P. Beaumont, and C.D.W. Wilkinson, Phys. Rev. Lett. **68**, 1754 (1992).

[12] A.K. Geim, T.J. Foster, A. Nogaret, N. Mori, P.J. McDonnell, N. LaScala, P.C. Main, and L. Eaves, Phys. Rev. B **50**, 8074 (1994).

[13] T. Schmidt, R.J. Haug, V.I. Fal'ko, K.v. Klitzing, A. Förster, and H. Lüth, Phys. Rev. Lett. **78**, 1540 (1997).

[14] T. Schmidt, P. König, E. McCann, V.I. Fal'ko, and R.J. Haug, Phys. Rev. Lett. **86**, 276 (2001).

[15] N.B. Zhitenev, R.C. Ashoori, L.N. Pfeiffer, and K.W. West, Phys. Rev. Lett. **79**, 2308 (1997).

[16] A. Nauen, J. Könemann, U. Zeitler, F. Hohls, and R.J. Haug, Physica E (Amsterdam) **12**, 865 (2002).

[17] P. Dutta and P.M. Horn, Rev. Mod. Phys. **53**, 497 (1981).

[18] M.J. Kirton and M.J. Uren, Adv. Phys. **38**, 367 (1989).

[19] A. van der Ziel, *Noise in Solid State Devices and Circuits* (Wiley, New York, 1986).

[20] G. Kiesslich, A. Wacker, E. Schöll, A. Nauen, F. Hohls, and R.J. Haug, Phys. Status Solidi C **0**, 1293 (2003).

[21] G. Kiesslich, A. Wacker, and E. Schöll, Phys. Rev. B **68**, 125320 (2003).

[22] Y.M. Blanter and M. Büttiker, Phys. Rev. B **59**, 10 217 (1999).